
GEOPHYSICS

A First Examination of the Helical Nature of Tropical Cyclogenesis¹

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Presented by Academician G. S. Golitsyn March 18, 2010

Received March 24, 2010

DOI: 10.1134/S1028334X1009031X

1. In this paper we conduct a novel investigation of tropical cyclone genesis and intensification from the perspective of helical features of atmospheric flows of different scales, which contribute to the organization of the cyclone. Using the data from a near cloud-resolving numerical simulation, helical characteristics of the velocity field are calculated and analyzed during a process of formation of tropical depression vortex and its subsequent intensification up to a mature hurricane stage. An evolution of large-scale vortex instability is followed, which develops on the background of intense cloud moist convection. The instability progresses by merging of small-scale helical convective structures and results in the formation of larger and more intense spiral vortices. Distributions of helicity, kinetic energy and enstrophy have been obtained. It has been discovered that the process is accompanied by a break of the reflection symmetry of three dimensional moist convective turbulence that is manifested in the generation of nonzero mean helicity. With such a break of symmetry a theoretical hypothesis is proposed to explain the self-organization of atmospheric processes under specific features of helical turbulence, which provide an energy transfer from small-scales structures to larger vortices. The goal of this collaborative Russian–American investigation, which started recently, is a clarification of the role of helicity in tropical cyclogenesis and intensification.

To mathematically describe the helical features of atmospheric flows it is useful to examine a well-known fluid-dynamical characteristic of such flows, called helicity of the velocity field [1]. Helicity of the velocity

field is a pseudoscalar quantity defined as the dot product of velocity and vorticity vectors (see, e.g., review article [2] and references therein on helicity and helical turbulence). A volume integral calculated in a specific space domain

$$H = \int \mathbf{v} \cdot \text{rot} \mathbf{v} d\mathbf{r} \quad (1)$$

gives the total helicity of vortex system. A non-vanishing mean helicity, $\langle H \rangle \neq 0$, implies the symmetry break of turbulence with respect to coordinate system reflections [3]. Its sign determines the predominance of the left-handed or the right-handed spiral motions. For instance, positive mean helicity will be generated in the moist atmosphere under the predominance of cyclonic updrafts and/or anticyclonic downdraft motions. Similarly, negative helicity will be generated for the case of anti-cyclonic updrafts and/or cyclonic downdraft flows.

In tropical cyclone investigations, helical features of the velocity field have not been highlighted until very recently. As far as we are aware, only papers [4–7] can be indicated on this subject. In [4, 5] calculations of helicity for mature hurricanes were carried out by regional atmospheric models whose space resolution did not allow resolving the most energetic scales of cumulus cloudiness, while in [6, 7] an analysis of helicity values was performed in the context of its possible role in increasing the ability of developing hurricane to resist the negative impact of the ambient vertical wind shear. In papers [6, 7] helicity was calculated using tropospheric-deep dropsonde soundings carried out by reconnaissance aircrafts under investigations of eight tropical cyclones of 1998–2001 seasons during wide-ranging campaign CAMEX (Convection and Moisture Experiment) [8] organized by NASA (National Aeronautics and Space Administration).

There exists a great amount of investigations concerned with examining the role of cloud convection (without consideration of its helical features) in tropical cyclone formation. There is a growing consensus that deep cumulonimbus convection of 2–20 km horizontal scales, which transfers sensible and latent heat

¹This article was translated by the authors.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE MAR 2010		2. REPORT TYPE		3. DATES COVERED 00-00-2010 to 00-00-2010	
4. TITLE AND SUBTITLE A First Examination of the Helical Nature of Tropical Cyclogenesis				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Department of Meteorology, Monterey, CA, 93943				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

from the underlying surface throughout the troposphere layer in the tropics, represents the main mechanism to intensify a pre-existing cyclonic circulation on the atmospheric mesoscales (~ 200 km) to a vortex of hurricane strength [9–11]. However, at present, a clear consensus of opinion has not yet emerged concerning a scenario of such transformation and physical mechanisms contributing to it.

Nearly thirty years ago in paper [12] was proposed a mechanism for intensification and sustaining of large-scale vortex disturbances in the atmosphere due to energy transfer from small-scale helical convective turbulence—the so called turbulent vortex dynamo. Only recently has it become possible to test this hypothesis with a physically consistent data set. And only recently have studies been conducted to examine reasonably high horizontal resolution (~ 1 – 3 km of horizontal scale and less) numerical simulations of tropical cyclone formation that possess an adequate representation of both the deep cumulus and stratiform stages. Between these works [13] offered a new scenario of hurricane formation based on self-organization of convective processes in an otherwise favorable tropical environment. Although helical features of these simulated flows were not taken into consideration within the framework of paper [13], self-organization of vortical (!) convection was observed similar to “helical” scenario [2], namely, as an enlargement of vortex structures from the size of individual rotating cumulus clouds in the model, their induced concentration of absolute angular momentum on the system scale circulation, and their merging with each other to yield newly forming larger vortices and an intensifying circulation on the system scale.

In this work we use the velocity fields obtained in [13] to calculate and analyze helical characteristics of the cyclogenesis and intensification process for the problem as posed by [13].

2. A numerical approach for investigation of large-scale helical instability in the atmosphere was proposed in [14, 15] and first applied in a simpler case, namely, to simulate helical-vortex effects in laminar Rayleigh–Benard convection by use of an additional helical force. Simulation [14, 15] demonstrated qualitatively new effects which appeared in a crisis manner. A nonzero mean helicity $\langle H \rangle \neq 0$ of the flow was generated, and after exceeding some its value, the large-scale vortex instability appeared. A key role in the process the vertical component of velocity played, and the corresponding evolutionary equation in mathematical model [14, 15] closed a positive feedback loop. The instability evolution observed as an enlargement of horizontal scales of structures what happened by merging of helical vortex cells. The process was accompanied by flow intensification in newly forming larger vortices, similarly to that observed in atmospheric modeling [13], which was based on hydrothermodynamic equations for the atmosphere.

It should be particularly pointed out about a distinct enhancement of the heat transfer discovered in experiments [14, 15]. The heat flux through a layer increased with an increase in mean helicity of the flow. A sharp intensification of heat transfer observed after exceeding the threshold of stability, and later during the instability evolution, after each merging of vortex structures. Thus, the effectiveness of heat transfer increased due to two factors, namely, increase in the mean helicity and decrease in a cell number of the convective system. Such energetic expedience suggests to us that a most effective “removal” of accumulating heat might be possibly one of the reasons for “helical” self-organization of convection in tropical cyclogenesis.

3. In the present paper, ideas and methods proposed previously for calculations and analysis of helical characteristics [14, 15] are applied to post-processing of velocity fields obtained in [13] by use of numerical meteorological model RAMS (Regional Atmospheric Modeling System) developed at Colorado State University. Detailed information on the governing equations of hydro-thermodynamics of the atmosphere, parameterizations of turbulent processes, specific characteristics of the RAMS model configuration, initial and boundary conditions is given in paper [13] as well as references to corresponding works.

3.1. Let us note further a feature that is of crucial importance for the problem under consideration. The velocity fields used for calculations of helical and integral characteristics in this work were obtained in [13] by use of three-dimensional nonhydrostatic numerical modeling system comprising time-dependent equations for all three components of velocity (including the vertical one, see item 2 on this subject), pressure, potential temperature, total water mixing ratio, and cloud microphysics. RAMS utilizes an interactive multiple nested grid scheme which allows explicit representation of cloud-scale features within the finest grid while enabling a large domain size to be used, thereby minimizing the impact of lateral boundary conditions. For all numerical experiments [13] three nested grids were used. A standard radiation boundary condition was used at the lateral boundaries, which assumes that disturbances reaching the boundaries move as linearly propagating gravity waves. A standard Rayleigh friction layer was included at upper levels in order to minimize reflection of gravity waves from the top of the model. All microphysical, radiative, and diffusive parameters were the standard ones employed for tropical summer conditions [13]. The initial temperature distribution in [13] was the mean Atlantic hurricane season sounding which was representative of so-called “non-Saharan-air-layer” air.

3.2. We performed calculations and analysis of helical and integral characteristics for six of nineteen numerical experiments [13], which are presented in the table. For the purpose of expedience, postprocessing of the model data was carried out on the finest

RAMS numerical experiments [13] analyzed in this work

No.	Name of experiment	Max v (m s ⁻¹) at $z = 4$ km	Description of experiment
A1	Control	6.6	$\Delta x = \Delta y = 2$ km, SST ¹ = 29°C. Metamorphosis to surface vortex successful. Becomes miniature tropical cyclone by approximately 60 h. Mean near-surface tangential wind ~ 12 m s ⁻¹ at 24 h, and 46 m s ⁻¹ at 72 h.
A2	3 km	6.6	$\Delta x = \Delta y = 3$ km, SST = 29°C. Metamorphosis to surface vortex successful. Mean near-surface tangential wind ~ 13 m s ⁻¹ at 24 h, and 46 m s ⁻¹ at 72 h.
B3	CAPE-less ² (3 km)	6.6	$\Delta x = \Delta y = 3$ km, SST = 29°C. Low-level moisture decreased by 2 g kg ⁻¹ . Metamorphosis successful, but slower rate of development. Mean near-surface tangential wind ~ 9 m s ⁻¹ at 48 h.
C1	No vortex	—	$\Delta x = \Delta y = 3$ km, SST = 29°C. No initial vortex. No surface development whatsoever.
C3	Weak vortex	5.0	$\Delta x = \Delta y = 3$ km, SST = 29°C. Metamorphosis successful, but slower rate of development. Mean near-surface tangential wind ~ 9 m s ⁻¹ at 72 h. Circulation very asymmetric even at 72 h.
E1	Zero Coriolis	6.6	$\Delta x = \Delta y = 3$ km, SST = 29°C. Coriolis parameter set to zero ($f = 0$). Metamorphosis successful. Develop surface-concentrated vortex as in A1, but no subsequent intensification observed through 72 h.

Note: ¹ SST—Sea Surface Temperature.

² Convective Available Potential Energy.

computational grid for subsequent times with a time increment of 10 min during 72 h of numerical experiment. Characteristics were calculated in the computational domain of $276 \times 276 \times 20$ km in Cartesian coordinates (x, y, z) by use of uniform finite-difference grid with increments $\Delta x, \Delta y, \Delta z$. In all six experiments the vertical increment in the post analysis was identical and equal to 500 m; the horizontal increments were $\Delta x = \Delta y = 3$ km, except experiment A1 with $\Delta x = \Delta y = 2$ km.

3.3. To analyze the process of self-organization of moist atmospheric convection observed under conditions of tropical cyclogenesis as posed by [13], a set of helical characteristics was computed, as well as some other integral characteristics of the velocity field which were applied in [14, 15].

The following characteristics were calculated with a time increment 10 min during the whole 72-hours evolution of tropical cyclone to obtain results discussed in this paper: three-dimensional relative helicity density

$$H_{i,j,k} = (\mathbf{V} \cdot \text{rot} \mathbf{V})_{i,j,k}, \quad (2)$$

two other important characteristics of the velocity field—enstrophy and kinetic energy densities:

$$\varepsilon_{i,j,k} = \frac{1}{2}(\text{rot} \mathbf{V})_{i,j,k}^2, \quad E_{i,j,k} = \frac{1}{2}(\mathbf{V})_{i,j,k}^2, \quad (3)$$

as well as mean (volume-integrated) values of helicity, enstrophy and kinetic energy integrated over the whole computational domain $276 \times 276 \times 20$ km and normalized by number of grid points:

$$\langle H \rangle, \langle \varepsilon \rangle, \langle E \rangle. \quad (4)$$

4. Before we begin the discussion of results, it is helpful to remember the characteristic values of wind

velocity for three stages of tropical cyclone strength so we may readily compare them with data in the table. At the stage of tropical depression the velocity of near surface tangential wind does not exceed 17 m s⁻¹, velocity values within 17–33 m s⁻¹ correspond to the tropical storm, more than 33 m s⁻¹ to the hurricane strength.

In numerical experiments A1, A2, B3, C3, and E1 from [13] a transformation of an initial mid-tropospheric vortex disturbance into a surface-concentrated tropical depression vortex was observed. Some unforeseen differences in both duration of the process and intensity of the formed vortex were found between these experiments. However, experiment E1, in the absence of the Coriolis force, did not reveal any further intensification of the surface-concentrated vortex during 72 h. In case C1, without an initial vortex disturbance, no system-scale surface development was observed.

In experiments A1, A2, B3, and C3 an influence of different factors (horizontal resolution, convective process, intensity of initial vortex) on cyclogenesis was studied, and similar tendencies were observed in evolution of helicity, enstrophy and kinetic energy.

Let us now discuss the results of numerical experiment A2 “3 km.”

Under examination of evolution of three dimensional helicity field (2), vertical velocity and vertical vorticity were analyzed also. This study readily allowed an identification of the formation of convective structures and determining their rotational signature, i.e., cyclonic or anticyclonic.

The undertaken modeling study showed the existence of intense helical convection, whose ascending

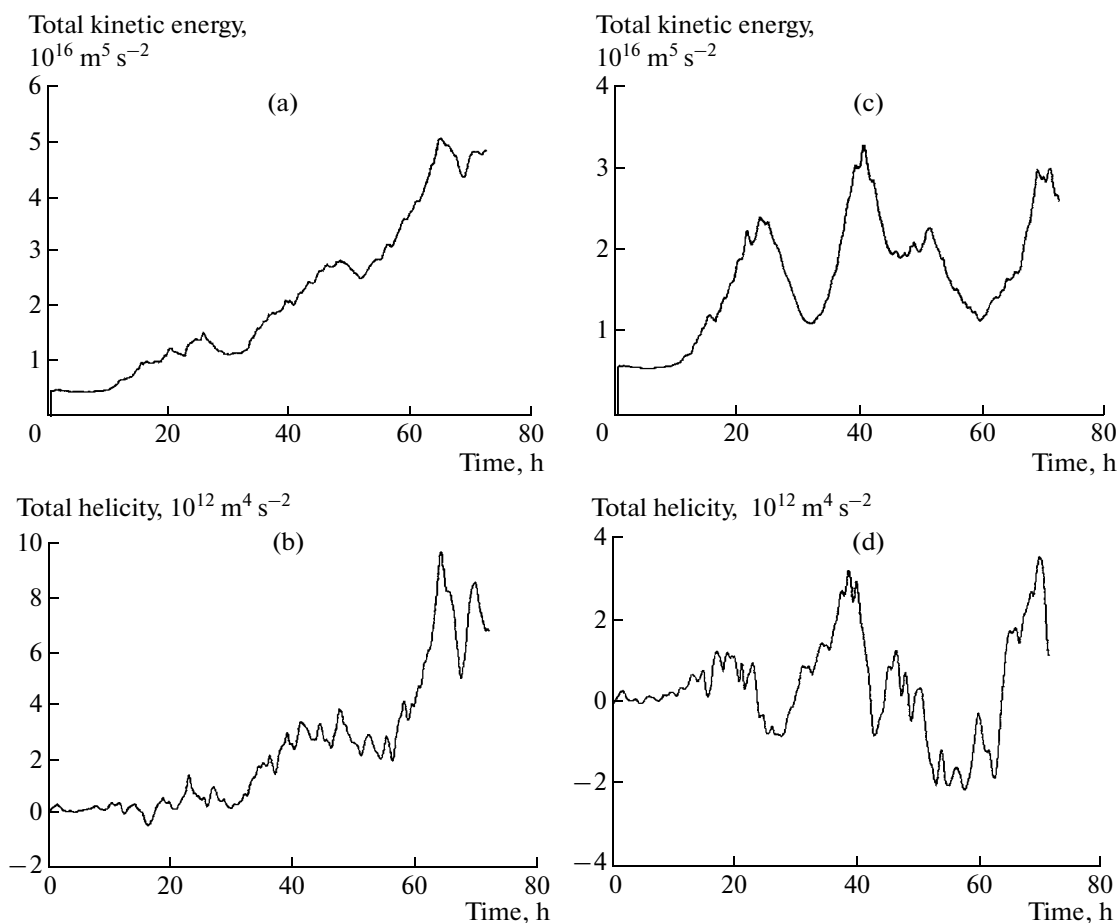


Fig. 1. Evolution of kinetic energy and helicity integrated over the computational domain and normalized by number of grid points: experiment A2 (left column—(a, b)), experiment E1 (right column—(c, d)).

vertical velocities sometimes exceeded 30 m s^{-1} during a portion of the numerical experiment, starting near $t = \sim 10\text{--}15 \text{ h}$ [13]. We observed the predominance of convective vortex structures with cyclonic rotation of ascending flow (i.e., positive helicity). A spectrum of convective motions was clearly observed, whose horizontal scales changed from 4–9 up to 15–30 km, while local helicity values in them were $0.002\text{--}0.004 \text{ m}^2 \text{ s}^{-2}$. The most intense of these structures reached through the bulk of the troposphere. Hot vortical plumes that rise through the bulk of the troposphere have been called “vortical hot towers.” Shortly after, a process of convective vortices merging started, and structures whose horizontal sizes reached 10–30 km were dominated, their helicity exceeded $0.008 \text{ m}^2 \text{ s}^{-2}$. During the process of merging one could observe an increase in the background helicity in adjacent areas.

As a result of further subsequent mergers, a surface-concentrated vortex of tropical depression strength (with mean tangential wind about 13 m s^{-1}) formed after 24 h of simulation. During further development into a hurricane power vortex (46 m s^{-1} at $t = 72 \text{ h}$)

even more intense vortical hot towers appeared, they possessed helicity values of $0.5\text{--}1.0 \text{ m}^2 \text{ s}^{-2}$.

Evolution of kinetic energy and helicity, calculated by use of (4), during the process of hurricane formation is shown in Figs. 1a, 1b. Enstrophy behavior is qualitatively similar to that observed for kinetic energy in Fig. 1a.

All pictures distinctly show an initial period of approximately 10 h, which is needed for development of intense small-scale helical convection and starting of the process of merging of convective structures. During next 10–15 h, a self-organization process continues and leads to formation of tropical depression vortex which has essentially larger scales. A local peak in all pictures corresponds to this event at approximately 24–25 h. Further intensification of tropical depression up to hurricane power till the end of simulation time at 72 h can be traced as a strong increase in kinetic energy and helicity values.

It should be pointed out that between the three integral characteristics of the velocity field, only helicity demonstrates qualitatively different behavior. During the first 15–17 h the integral helicity is close to

zero, and there exist short time periods when it becomes negative. After approximately 18 h of simulation time helicity becomes distinctly positive and increasing. Analysis of vertical velocity and vertical vorticity for these conditions shows that such positive helicity is a result of the predominance of locally cyclonic updrafts. Non-zero helicity means a break of the mirror symmetry of atmospheric turbulence what may result in generation of a large-scale instability [3].

It is instructive to compare the kinetic energy and helicity evolution in this experiment A2 (Figs. 1a, 1b) against that of experiment E1, the absence of the Coriolis force (Figs. 1c, 1d). In the latter case when the surface-concentrated vortex forms, there is no further intensification. As we can see, in scenario E1 the helicity behavior is cardinally different: the oscillations are of significant amplitude, and are even accompanied by a change of sign when the largest positive and negative values are comparable to their absolute values.

It is important to point out that the values of positive helicity generated in experiment A2, which resulted in hurricane formation, are more than two times higher than positive helicity values in case E1. Furthermore, no change in the sign in helicity is observed in A2 after the tropical depression stage is attained.

The results presented portray an important signature of integrated helicity in the evolution of large-scale vortex instability. They clearly motivate further investigations of spectral characteristics of helical moist convective atmospheric turbulence in conditions of tropical cyclogenesis.

The practical significance of these investigations is connected with a possibility to use helicity as an indicator of large-scale vortex instability.

ACKNOWLEDGMENTS

We would like to thank G.S. Golitsyn, L.Kh. Ingel, M.V. Kurgansky, P.G. Frick, and O.G. Chkhetiani for stimulating discussions. G.L. is grateful to S. Barve,

M.E. Nicholls, and R.A. Stepanov for their help and consultations in organization of numerical simulation. This work was supported by the Russian Foundation for Basic Research (project no. 10-05-00100), by the U.S. National Science Foundation under grant ATM-0733380, and the International Science and Technology Center (project no. 3726).

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